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# A METHOD FOR DETERMINING DYNAMIC STRESS INTENSITY FACTORS FROM COD MEASUREMENT AT THE NOTCH MOUTH IN DYNAMIC TEAR TESTING

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Abstract:

A formula is derived for determining dynamic stress intensity factors directly from crack mouth opening displacements in dynamic tear test specimen. The results obtained by the present estimation method for stationary as well as propagating cracks agree excellently with those directly obtained through a highly accurate moving-singularity finite element method. The present method can also be applied for other types of specimen which have a relatively short edge crack without any loading on the crack surface. The present simple estimation method should be of great value in the experimental measurement of dynamic stress-intensity factors for propagating cracks in (opaque) structural steel dynamic tear test specimens.

* Research Scientist II
** Regents' Professor of Mechanics

Proposed Estimation Method:

There is a major difficulty to determine experimentally the dynamic stress intensity factors for a propagating crack in a non-transparent (metallic) fracture specimen under the conditions of impact loading as well as quasi-static loading. For a transparent (photoelastic) specimen, dynamic stress intensity factors can be measured by means of the optical method such as the photoelastic method [1] or the shadow optical method of caustics [2]. On the other hand, for a non-transparent specimen, so far, only one attempt has been made for determining dynamic stress intensity factors directly from the shadow optical method of caustics [3]. This was done by measuring the light reflected from the mirrored surface of the high strength steel specimen with a dynamically propagating crack under conditions of quasi-static loading. However, the experimental results show large oscillations of stress intensity factor with high frequencies. These oscillations are attributed to the high frequency stress waves which may exist only on the surface of the specimen. This situation may become more critical in the impact test specimen.

In the present note, a simple method is developed for determining dynamic stress intensity factors directly from the measurement of crack opening displacement at the notch mouth in dynamic tear testing. A formula for the relation between dynamic stress intensity factor and crack opening displacement at the notch mouth is derived by using the relation in the static case. This possibility was found from a critical examination of the results for several numerical fracture simulations made in Ref. [4]. The moving-singularity element procedure used in Ref. [4] gives a direct evaluation of the dynamic stress intensity factors for a propagating as well as stationary crack.

The notations, and dimensions of the dynamic tear test specimen, are shown in Fig. 1. The specimen geometry and material properties correspond to those

reported in Ref. [5]. In the finite element analysis [4], the following initial conditions were used: at time t=0, velocity $\dot{u}_T$=6.88 m/sec. The tup displacement is calculated by $\bar{u}_T=\dot{u}_T t$. The displacements at the supports are fixed for all the times. In Ref. [4], the influence of the loss of contact of the specimen at various times with either the tup or the supports has also been investigated. However, we shall focus our attention to the case when the specimen is in contact with the tup and the supports. A plane-strain condition is invoked in the two-dimensional analysis.

The crack propagation history is assumed as shown in Fig. 2. This crack propagation history was used as input data for the "generation phase" fracture simulation. As shown in Fig. 2, the crack is stationary (C=0) until t=95 μsec, during the period of 95 to 146 μsec the crack propagates with the speed of 375 m/sec, and after 146 μsec the crack speed becomes 95 m/sec.

The crack opening profiles as well as the dynamic stress intensity factors at various times, obtained by the dynamic finite element analysis [4], are shown in Fig. 3. As seen from the figure the profiles are nearly linear except very near the crack-tip. To compare with the static case which does not include the inertia effect, a series of static analyses is perfomred, with the boundary conditions and crack lengths corresponding to those in the dynamic analysis [4] at the various times. Fig. 4 shows the crack opening profiles in the static case. Comparing Figs. 3 and 4, it is seen that the crack profiles for the both cases are very similar, but with different amounts of crack opening, at the respective times.

To seek a correlation between the dynamic and static cases, the following coefficient is introduced as

$$[illegible] = K_I/[illegible] \quad (1)$$

where [illegible] is the crack-mouth opening (Fig. 1). For a given specimen size, this

coefficient depends on not only the crack length but also the crack speed for the dynamic case, while the coefficient is a function of only the crack length for the static case. The variation of the coefficients for both the static and dynamic cases is shown in Fig. 5. An excellent linear correlation can be seen in the figure. This correlation suggests the applicability of the coefficient obtained by the static analysis to the evaluation of dynamic stress intensity factors.

First we shall seek the relation between the static stress intensity factor and the crack mouth opening displacement. According to Tada's handbook [6], these are expressed as

$$K_I = \frac{3PS}{2W^2}\sqrt{\pi a}\,F(a/W) \tag{2}$$

$$\delta = \frac{6PSa}{E'W^2}V(a/W) \tag{3}$$

where $E'=E$ for plane stress and $E'=E/(1-\nu^2)$ for plane strain. From the above equations, the static stress intensity factor can be expressed in terms of the crack mouth opening displacement $\delta$:

$$K_I = C_s \cdot \delta \tag{4}$$

with

$$C_s = \frac{E'\sqrt{\pi}}{4\sqrt{W}}U(a/W) \tag{5}$$

where

$$U(a/W) = (a/W)^{-\frac{1}{2}}F(a/W)/V(a/W) \tag{6}$$

The functions $F(a/W)$ and $V(a/W)$ have been reported by various investigators. Among them, the handbook [6] gives the following formulae:

for $S/W = 4.0$

$$F(a/W) = 1.090 - 1.735(a/W) + 8.20(a/W)^2 - 14.18(a/W)^3 + 14.57(a/W)^4$$
$$(0 \le a/W \le 0.6) \tag{7}$$

$$V(a/W) = 0.76 - 2.28(a/W) + 3.87(a/W)^2 - 2.04(a/W)^3$$
$$+ \frac{0.66}{(1-a/W)^2}$$
$$\text{(any } a/W) \tag{8}$$

and for pur bending ($S/W=\infty$);

$$F(a/W) = \sqrt{\frac{2}{\pi}\frac{a}{W}\tan\left(\frac{\pi}{2}\frac{a}{W}\right)} \cdot \frac{0.923+0.199\{1-\sin(\frac{\pi}{2}\frac{a}{W})\}^4}{\cos(\frac{\pi a}{2W})}$$
$$\text{(any } a/W) \tag{9}$$

$$V(a/W) = 0.8 - 1.7(a/W) + 2.4(a/W)^2 + \frac{0.66}{(1-a/W)^2}$$
$$\text{(any } a/W) \tag{10}$$

The function $U(a/W)$ can be calculated by substituting Eqs. (7) and (8), or Eqs. (9) and (10) in Eq. (6). Since Eq. (7) is invalid for $a/W>0.6$ and the function $U(a/W)$ is less sensitive to the normalized span length $S/W$, the formulae for pure bending, Eqs. (9) and (10), are used to calculate the function $U(a/W)$, in the present paper.

The variation of the function $U(a/W)$ with the normalized crack length is shown in Fig. 6. Dynamic stress intensity factors for a stationary crack under the impact loading condition can be estimated from Eq. (4), by substituting a value of $U(a/W)$ and the experimentally measured $\delta$.

However, for a dynamically propagating crack, because of the influence of the crack speed on the displacement field near the crack-tip, a crack speed correction factor is required to determine the stress intensity factors. The crack opening displacement near a propagating crack-tip is expressed as [7]:

$$v_{(\theta=\pi)} = \frac{K_{ID}}{G}\left(\frac{r}{\pi}\right)^{\frac{1}{2}}\sqrt{2}\,A(c) \tag{11}$$

where $K_{ID}$ is the stress intensity factor for dynamically propagating crack,

G is the shear modulus, r is the distance from the crack-tip, and A(c) is a dimensionless function of the crack speed. For isotropic materials, the factor A(c) is given by

$$A(c) = \frac{\beta_1(1-\beta_2^2)}{4\beta_1\beta_2 - (1+\beta_2^2)^2} \tag{12}$$

$$\beta_j = \sqrt{1-(c/c_j)^2}; \; j=1,2 \tag{13}$$

The wave velocities $c_1$ and $c_2$ are given by

$$c_1 = \sqrt{\frac{\kappa+1}{\kappa-1}\frac{G}{\rho}} \tag{14}$$

and

$$c_2 = \sqrt{\frac{G}{\rho}} \tag{15}$$

with

$$\kappa = \begin{cases} 3-4\nu & \text{for plane strain} \\ (3-\nu)/(1+\nu) & \text{for plane stress} \end{cases} \tag{16}$$

In the limit when c=0, the value of the function is given by

$$A(0) = \frac{\kappa+1}{4} \tag{17}$$

If we substitute Eq. (17) into Eq. (11), Eq. (11) becomes identical to the crack opening displacement for a stationary crack in a static or elastodyanamic field. Comparing both the stationary and propagating cracks, we obtain the following relation:

$$K_{ID} = \frac{A(0)}{A(c)} K_I \tag{18}$$

Thus, the stress intensity factor for a propagating crack can be determined in terms of experimentally measured $\delta$ as

$$K_{ID} = C_D \cdot \delta \tag{19}$$

with

$$C_D = \frac{E'\sqrt{\pi}}{4\sqrt{W}} \; U(a/W) \; . \; B(c) \tag{20}$$

where B(c) is the crack speed correction factor and given by

$$B(c) = A(0)/A(c) \tag{21}$$

The variation of the factor B(c) under the plane strain condition, with the normalized crack speed (normalized by the shear wave speed) is shown in Fig. 7. The factor B(c) versus $c/c_2$ curves depend only on the Poisson's ratio. The value of B(c) becomes zero at $c=c_R$ where $c_R$ is the Rayleigh wave speed. If the crack speed is relatively slow, i.e., $c \leq 0.15c_2$, a value of 1 can be used for the crack speed correction factor B(c) allowing an error within 2%.

In order to demonstrate the applicability of the present method, the crack mouth opening displacements obtained in Ref. [4] are used. Fig. 7 shows the variations of stress intensity factors obtained from different techniques. In Fig. 7, the solid line shows the stress intensity factor determined directly as a variable in the moving-singularity element procedure [4], and the dotted line shows that calculated by Eq. (19) substituting the crack mouth opening displacements determined in Ref. [4]. As demonstrated in Ref. [3], the moving-singularity finite element method gives very accurate dynamic stress intensity factors. As seen from the figure the present estimation procedure, Eqs. (19, 20), yields results which agree excellently with those of the moving-singularity element procedure[4] when the crack is stationary. When the crack propagates, however, the overall variation of the presently estimated result is good, although the estimated result appears to oscillate slightly around the result of the moving singularity element procedure [4]. For a given material, it is noted that the present simple-estimation method gives better results for a shorter crack.

For other types of specimen which have a relatively short edge crack without any loading on the crack surface, the present method can also be applied

to determine the dynamic stress intensity factors from the mouth opening displacements of the propagating crack.

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Figure Captions:

Fig. 1: Dynamic tear test specimen

Fig. 2: Crack growth history

Fig. 3: Crack opening profiles in the dynamic case

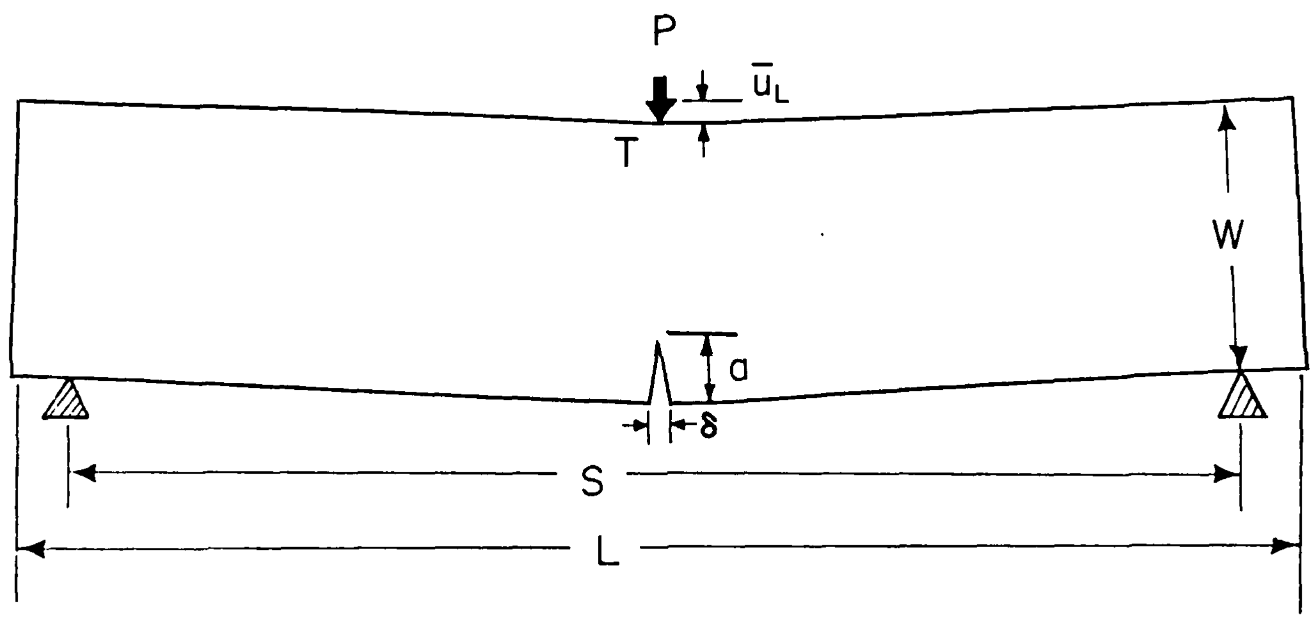
Fig. 4: Crack opening profiles in the static case

Fig. 5: Variation of the coefficients $C(=K_I/\delta)$ in the dynamic and static cases

Fig. 6: Function of crack length $U(a/W)$

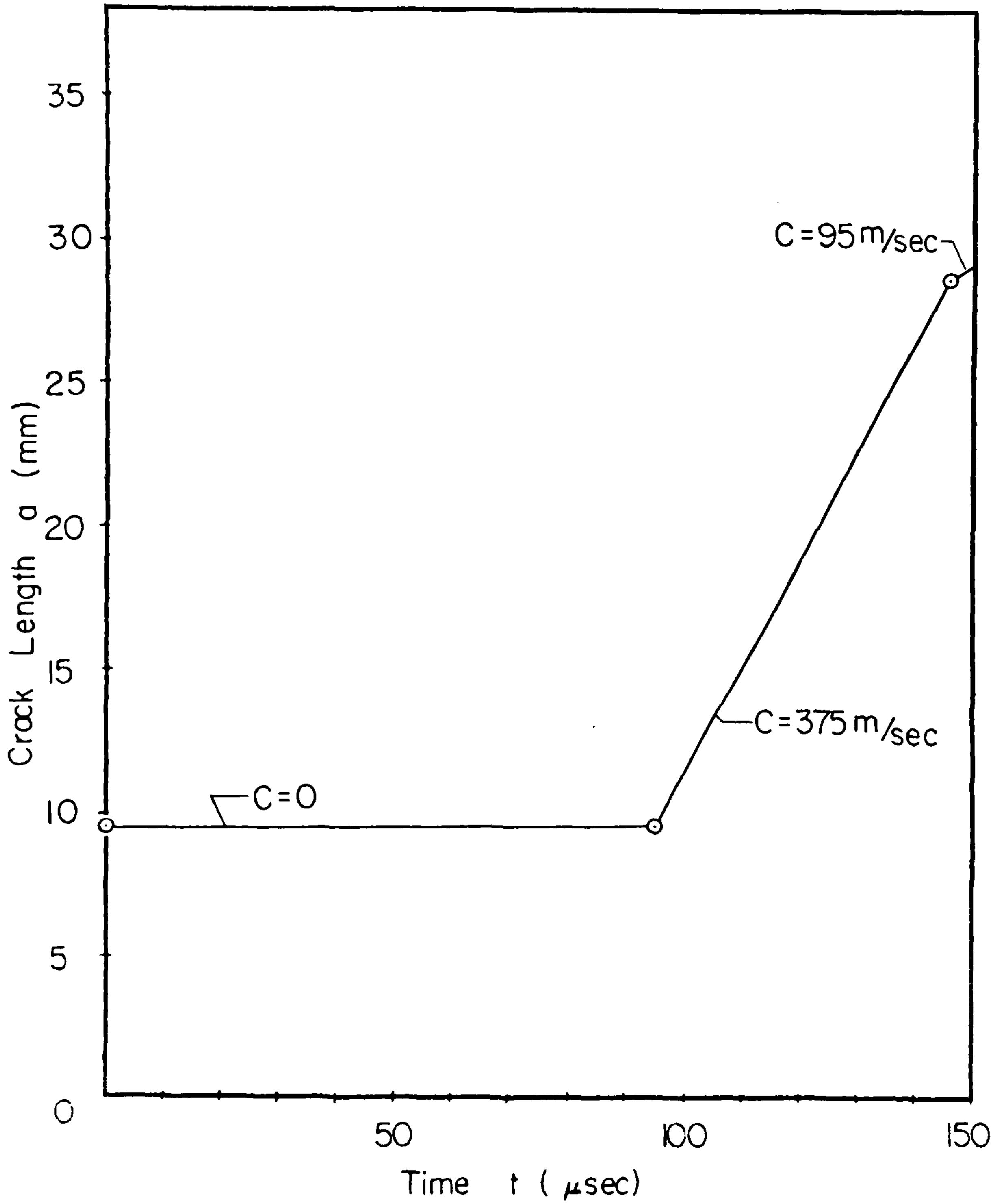
Fig. 7: Crack speed correction factor $B(c)$

Fig. 8: Comparison of dynamic stress intensity factors



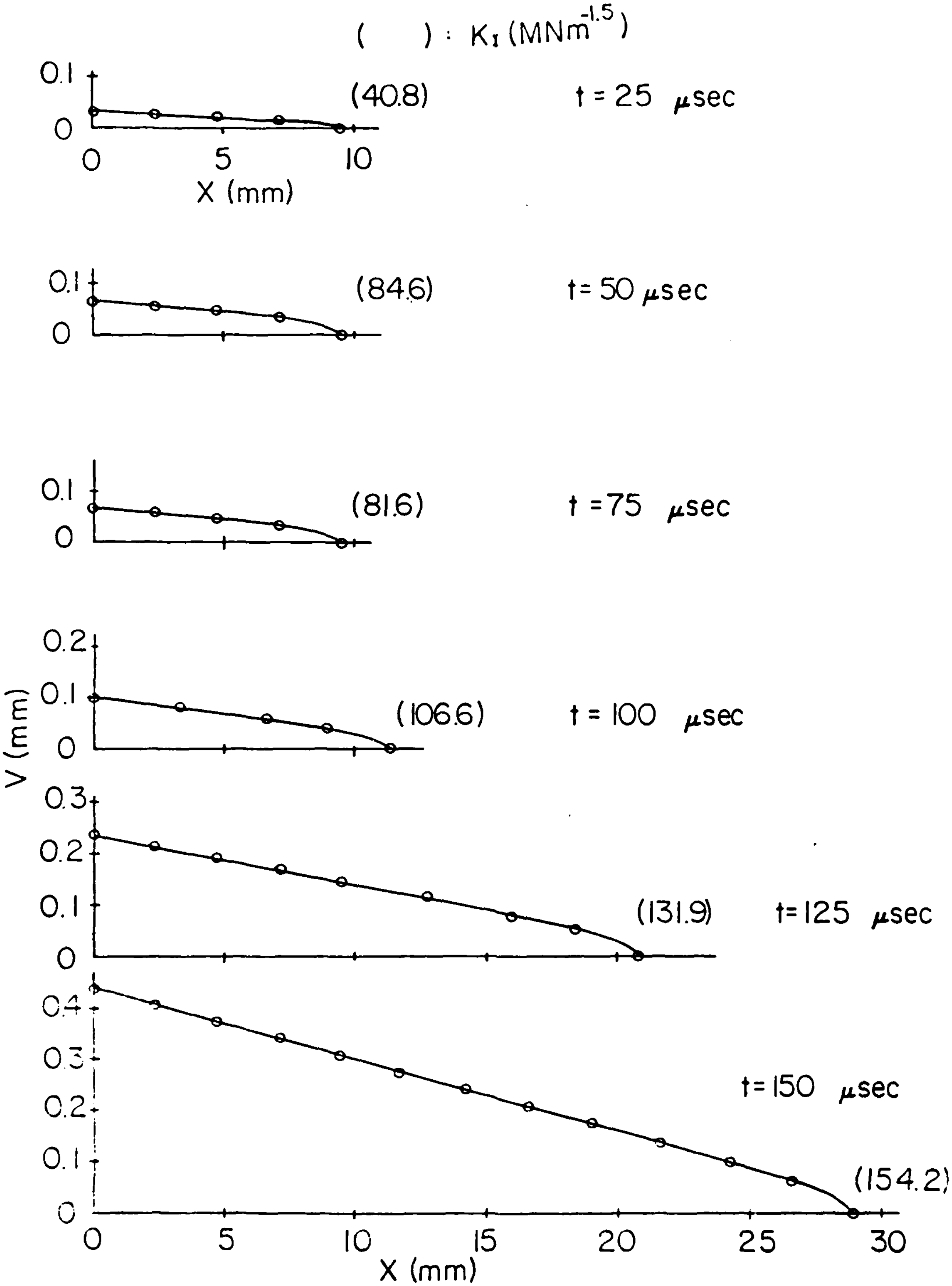

| | | | |
|---|---|---|---|
| Length | $L = 181$ mm | Initial Crack Length | $a_o = 9.5$ mm |
| Span | $S = 165$ mm | Young's Modulus | $E = 200$ GPa |
| Width | $W = 38$ mm | Poisson's Ratio | $\nu = 0.28$ |
| Thickness | $B = 15.8$ mm | Mass Density | $\rho = 7840$ Kg/m$^3$ |

Fig. 1



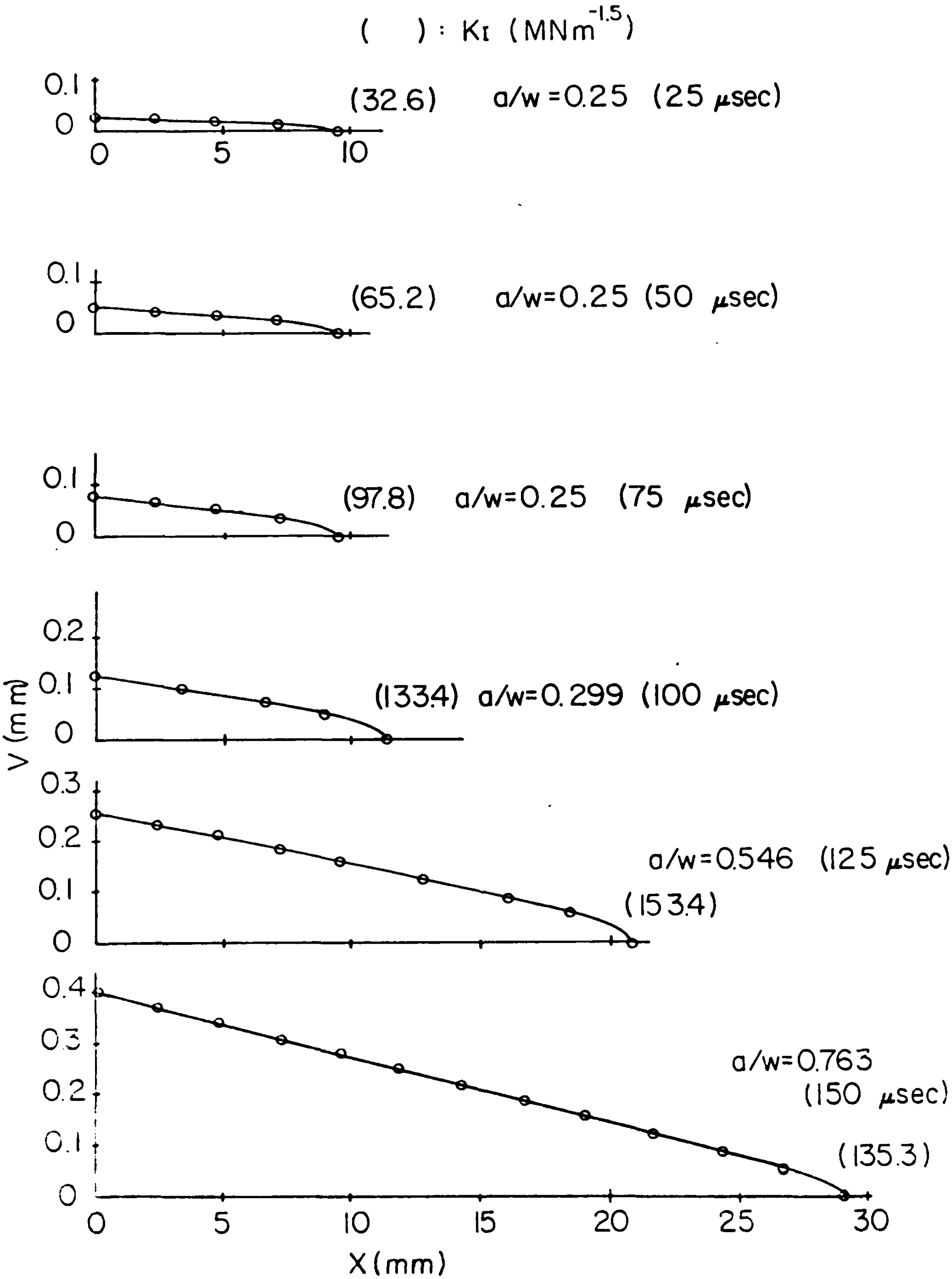
Crack Length a (mm)
Time t ( μsec)
0
5
10
15
20
25
30
35
50
100
150
C=0
C=375 m/sec
C=95 m/sec


Fig. 2



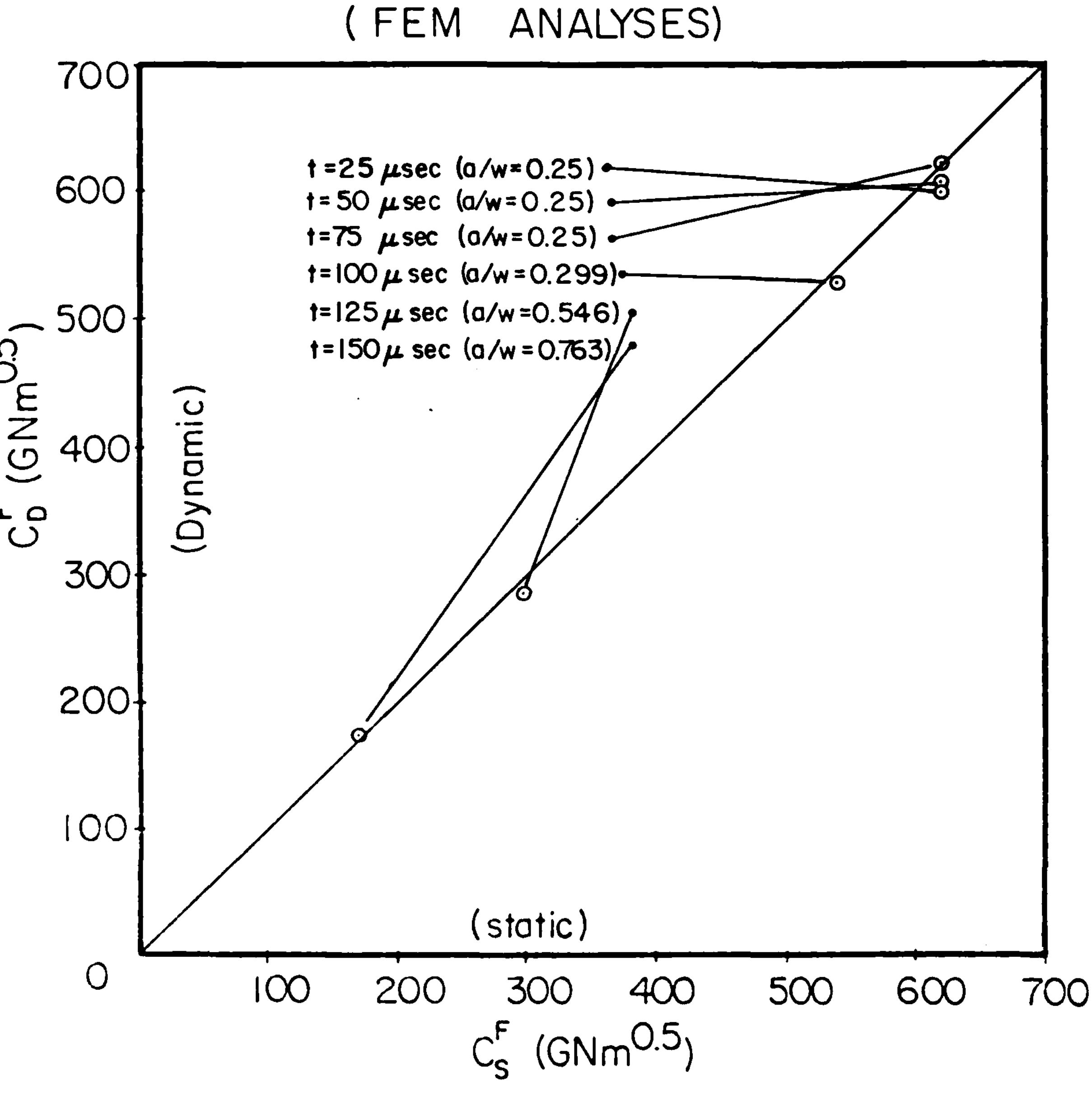
DYNAMIC ANALYSIS

Fig. 3



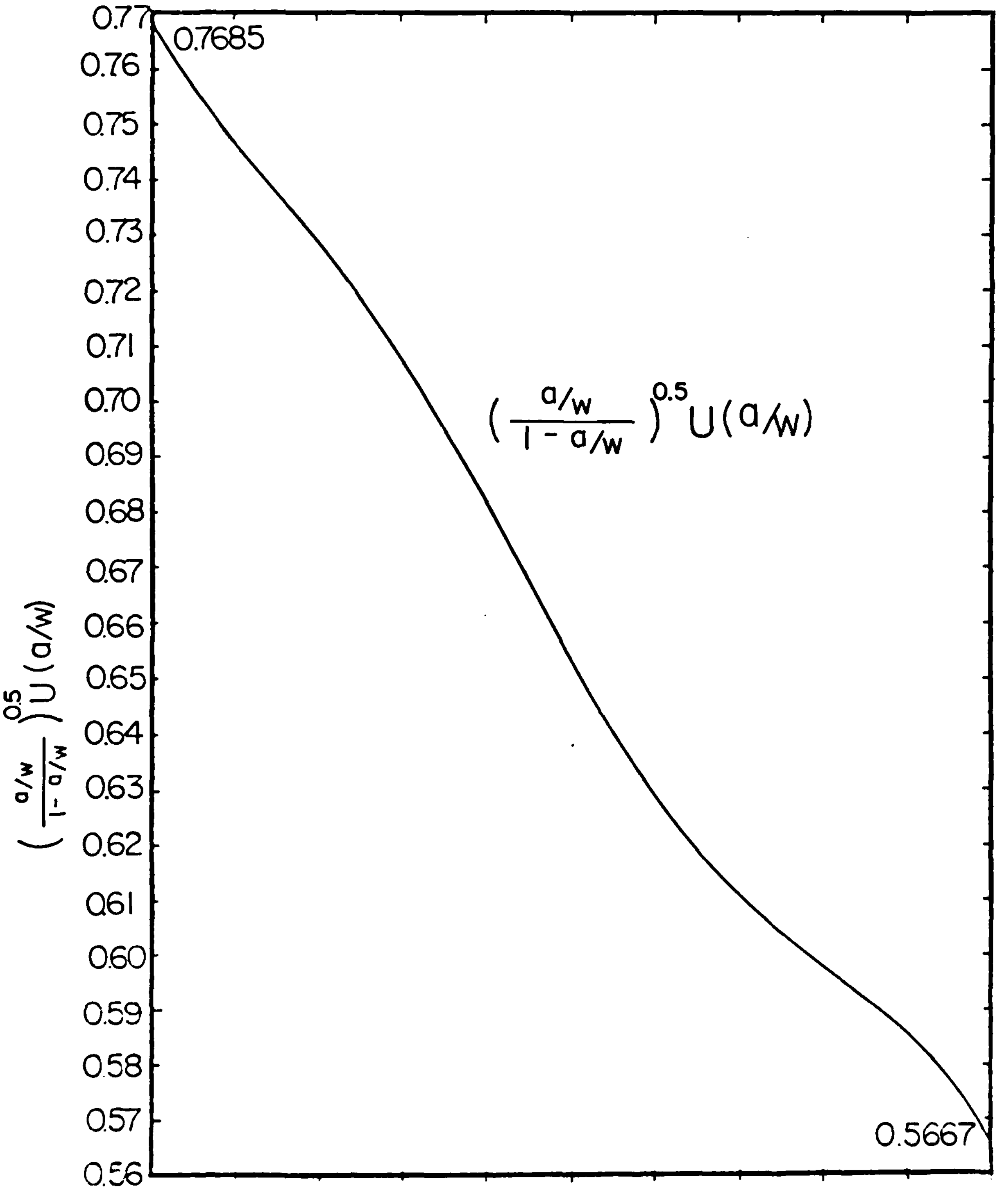

STATIC ANALYSIS

Fig. 4



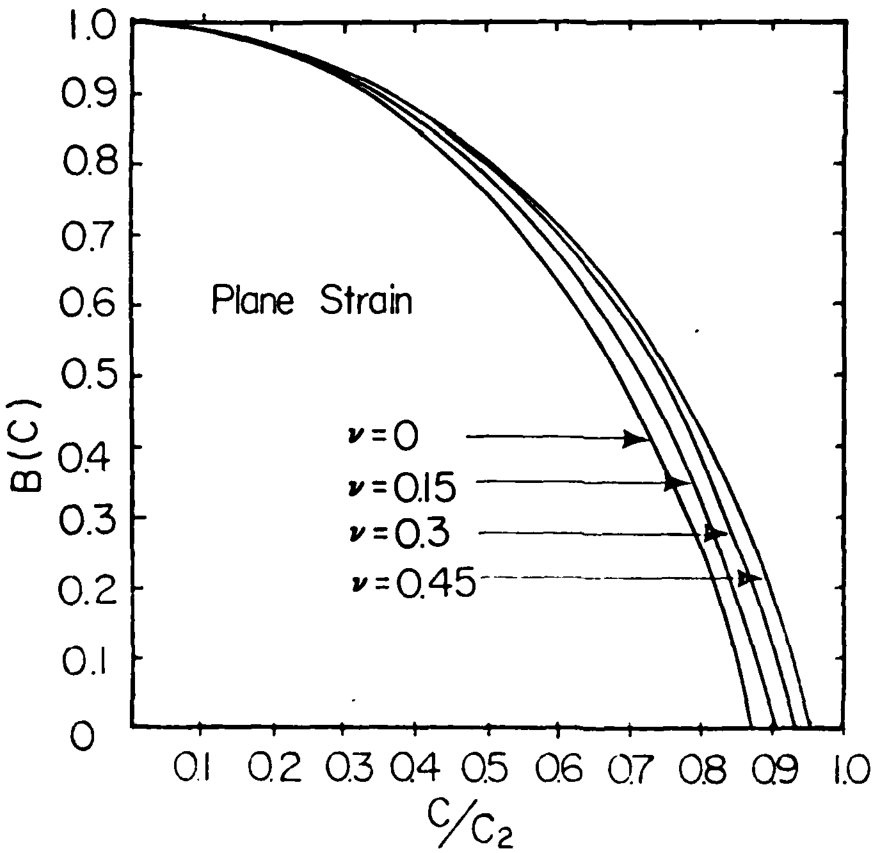
( FEM ANALYSES)
t=25 μsec (a/w=0.25)
t=50 μsec (a/w=0.25)
t=75 μsec (a/w=0.25)
t=100 μsec (a/w=0.299)
t=125 μsec (a/w=0.546)
t=150 μsec (a/w=0.763)
(Dynamic)
(static)
$C_D^F$ (GNm$^{0.5}$)
$C_S^F$ (GNm$^{0.5}$)
0
100
200
300
400
500
600
700


Fig. 5



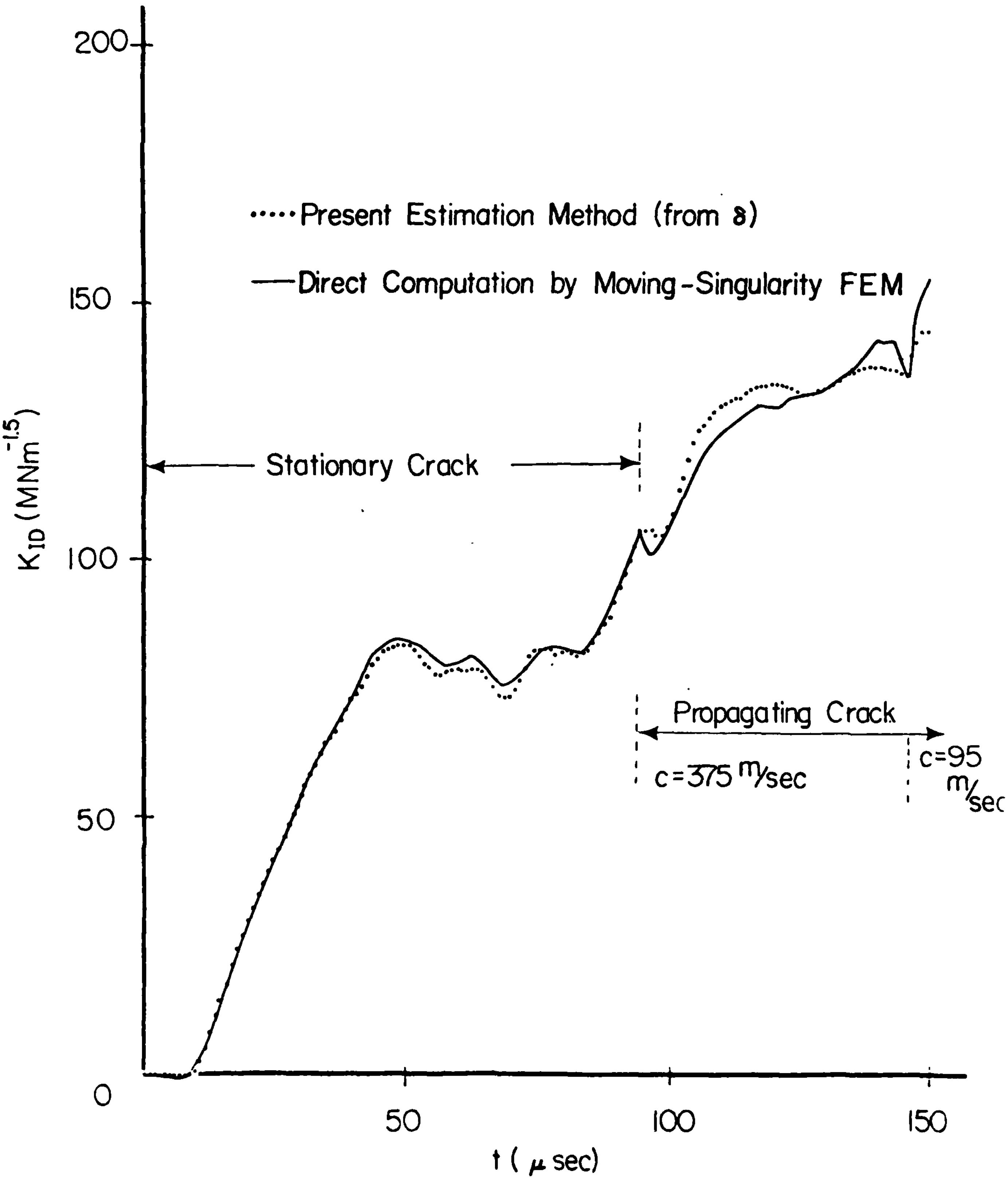
0.77
0.76
0.75
0.74
0.73
0.72
0.71
0.70
0.69
0.68
0.67
0.66
0.65
0.64
0.63
0.62
0.61
0.60
0.59
0.58
0.57
0.56
0.7685
0.5667
$\left(\frac{a/w}{1-a/w}\right)^{0.5} U(a/w)$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
a/W


Fig. 6



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
B(C)
Plane Strain
ν = 0
ν = 0.15
ν = 0.3
ν = 0.45
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
C/C2


Fig. 7



200
150
100
50
0
$K_{ID}$ (MNm$^{-1.5}$)
····Present Estimation Method (from δ)
—Direct Computation by Moving-Singularity FEM
Stationary Crack
Propagating Crack
c=375 m/sec
c=95 m/sec
50
100
150
t ( μ sec)


Fig. 8

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dynamic stress-intensity factors of propagating cracks in (opague) structural steel dynamic tear test specimens.

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